

Open charm scenarios

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Abstract. We discuss possibilities of identifying open charm effects in direct production processes, and propose that direct evidence for the open charm effects can be found in $e^+e^- \rightarrow J/\psi\pi^0$. A unique feature with this process is that the $D\bar{D}^* + c.c.$ open channel is located in a relatively isolated energy, i.e. ~ 3.876 GeV, which is sufficiently far away from the known charmonia $\psi(3770)$ and $\psi(4040)$. Due to the dominance of the isospin-0 component at the charmonium energy region, an enhanced model-independent cusp effect between the thresholds of $D^0\bar{D}^{*0} + c.c.$ and $D^+D^{*-} + c.c.$ can be highlighted. An energy scan over this energy region in the e^+e^- annihilation reaction can help us to understand the nature of $X(3900)$ recently observed by Belle Collaboration in $e^+e^- \rightarrow D\bar{D} + c.c.$, and establish the open charm effects as an important non-perturbative mechanism in the charmonium energy region.

1. Background

Our interests in the study of hadron spectroscopy are strongly motivated by the speculation of exotic hadrons of which the very existence is implicated by QCD. During the past decades, the search for exotic hadrons has been one of the most important physics goals at high-energy experimental facilities, such as Tevatron (CDF and DØ), B-factories (Belle and BaBar) and electron storage rings at CLEO and BES-III. Although confirmed evidence for exotics is still lacking, experimental measurements have brought a lot of surprises during the past few years. In the charmonium sector, a number of new resonance-like signals have been observed by the B-factories [1], and some of them exhibit peculiar decay modes which could be an indication for their being exotic hadrons [2, 3, 4]. Meanwhile, it should also be cautioned that some of those enhancements observed in experiment may not be genuine resonances. To identify those non-resonant structures and understand the underlying dynamics for their production and decays are of great importance for the study of hadron spectroscopy and gaining insights into the strong QCD.

The most updated summary of those newly-discovered resonance-like states can be found in the recent review article [4], among which the vector charmonium-like states are of our interests here. Firstly, the vector charmonium spectrum is well established in both theory and experiment in the low mass region. It has been a success of the potential quark model that the light charmonium states can be well described by the one-gluon exchange and linear confinement potentials [5, 6, 7]. So far, nearly all the light charmonia below the $D\bar{D}$ open threshold have been discovered in experiment [8]. The measured masses are in good agreement with the quark model predictions which suggests that the massive charm quark is a good effective degrees of freedom in the description of the charmonium spectrum. Secondly, an experimental advantage

with the vector charmonium states is that they can be directly produced in e^+e^- annihilations. This would allow a direct measurement of these states in experiment. As a consequence, the data would impose an immediate test of theoretical calculations.

Restricted to the vector charmonium sector, the experimental observations have turned out to be surprising. The first unexpected result was the observation of the charmonium-like vector $Y(4260)$ in its decay into $J/\psi\pi\pi$ by BaBar in the initial state radiation (ISR) process. It was later confirmed by Belle and CLEO. Meanwhile, several other charmonium-like vector states, $Y(4008)$, $Y(4360)$, and $Y(4660)$, were observed in the same ISR process and the same $J/\psi\pi\pi$ invariant spectrum. There have been tremendous theoretical interpretations for these states in the literature. Some of those states are proposed to be exotic candidates for which a detailed review can be found in Ref. [4].

Our focus in this proceeding is not on those above mentioned resonant structures. Instead, we are interested in an enhancement, the so-called $X(3900)$ ¹, observed in the ISR process by Belle in $e^+e^- \rightarrow \gamma(D\bar{D})$ [9]. The peak position of this enhancement is located at 3943 ± 21 MeV with a width of 52 ± 11 MeV. Several peculiar aspects make this structure extremely interesting and deserves to be studied in detail: i) In the vicinity of the $X(3900)$ mass region, there is no vector charmonium state predicted in the potential quark model. One notices that the nearby quark model states are $\psi(3770)(1D)$ and $\psi(4040)(3S)$ which fit well in the $c\bar{c}$ spectrum. This feature immediately implies that this structure cannot be easily accommodated by the quark model classifications. ii) A natural speculation is that such an enhancement is due to the $D\bar{D}^* + c.c.$ open threshold as anticipated by Eichten *et al.* [10] long time ago. However, theoretical description of the open threshold effects has suffered a lot from model-dependence. Thus, solid evidence that confirms the dynamical origin of $X(3900)$ is still desired.

In this proceeding, we report our recent progress on the study of the open threshold effects in $e^+e^- \rightarrow J/\psi\pi^0$, $J/\psi\eta$ and $\phi\eta_c$. We will show that model-independent evidence can be reached for the $D\bar{D}^* + c.c.$ open threshold in $e^+e^- \rightarrow J/\psi\pi^0$. As a consequence, it would be possible to stab the $X(3900)$ as the first evidence for the open threshold enhancement observed in experiment.

2. Identify the open threshold effects

2.1. Evidence for the $D\bar{D}^* + c.c.$ open threshold effects in $e^+e^- \rightarrow D\bar{D}$

It should be mentioned that the Belle Collaboration also reported their measurement of the cross section lineshape of $e^+e^- \rightarrow D\bar{D}^* + c.c.$ [11]. The same channels were also measured by the BaBar Collaboration [12] which appeared to be consistent with the Belle data. In Refs. [11, 12], a threshold enhancement is observed in the cross section around $W = 3.9$ GeV, which provides an important evidence for the role played by the $D\bar{D}^* + c.c.$ open threshold. By fitting the data of Ref. [11], in Ref. [13], we show that the $\gamma^*D\bar{D}^*$ form factor can be extracted based on the following two parameterizations:

(i) Form factor one (FF-I) for the $\gamma^*D\bar{D}^*$ coupling:

$$g_{\gamma^*D\bar{D}^*}(s) = g_1 \exp[-(s - (m_D + m_{D^*})^2)/t_1] + g_0, \quad (1)$$

where $x = 0$ corresponds to the $D\bar{D}^* + c.c.$ threshold, and g_1 , t_1 , and g_0 are fitting parameters.

(ii) Form factor two (FF-II) for the $\gamma^*D\bar{D}^*$ coupling:

$$g_{\gamma^*D\bar{D}^*}(s) = \left| \frac{b_0}{s - m_X^2 + im_X\Gamma_X} + b_1 \right|, \quad (2)$$

with a background term b_1 . The parameter b_0 can be regarded as the product of the γ^*X coupling and the $X D\bar{D}^*$ coupling.

¹ This structure is named as $G(3900)$ in Ref. [4].

Table 1. Parameters fitted with FF-I and FF-II for the $\gamma^* D\bar{D}^*$ effective coupling form factor. The data are from Belle [11].

FF-I		FF-II	
$g_{\gamma^* D\bar{D}^*} = g_1 \exp[-(s - (m_D + m_{D^*})^2)/t_1] + g_0$		$g_{\gamma^* D\bar{D}^*} = \frac{b_0}{s - m_X^2 + im_X \Gamma_X} + b_1 $	
g_1	8.86 ± 0.59	b_0	3.08 ± 0.31
t_1	1.28 ± 0.06	m_X (GeV)	3.943 ± 0.014
g_0	0.43 ± 0.02	Γ_X (MeV)	119.0 ± 10.0
		b_1	0.016 ± 0.045
$\chi^2/\text{d.o.f}$	68.86/53	$\chi^2/\text{d.o.f}$	47.67/52

The fitted parameters in these two parametrization schemes are listed in Table. 1. As shown in Fig. 1 by the dashed line, FF-I can perfectly describe the energy dependence of the effective coupling, and be extrapolated to the $D\bar{D}^*$ threshold. The dotted line indicates that the FF-II agrees with the data at higher energies, but drops at the threshold region. In Ref. [13], it was shown that the structure of $X(3900)$ in $e^+e^- \rightarrow D\bar{D}^*$ can be well described after taking into account the $D\bar{D}^* + c.c.$ open threshold effects [14]. However, one should realize that the open threshold effects are not the unique explanation for the structure of $X(3900)$. It can also be explained by a Breit-Wigner distribution as shown by the parametrization of FF-II. So the key question is, How would one be able to elucidate that the $X(3900)$ is caused by the $D\bar{D}^* + c.c.$ open threshold? The answer to this question may possibly come from reaction channel $e^+e^- \rightarrow J/\psi\pi^0$ as to be discussed later. Nevertheless, correlated processes including $e^+e^- \rightarrow J/\psi\eta$ and $\phi\eta_c$ would also bring additional information which can be examined in experiment.

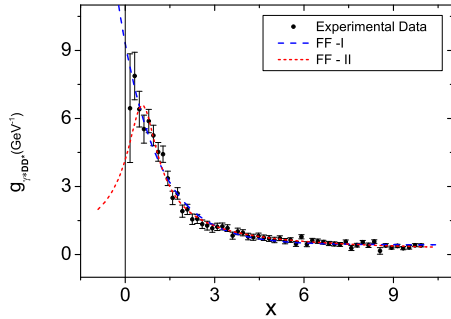


Figure 1. The x -dependence of $g_{\gamma^* D\bar{D}^*}$ extracted from the cross sections for $e^+e^- \rightarrow D^+D^{*-} + c.c.$ [11] with $x \equiv s - (m_D + m_{D^*})^2$. The dashed and dotted line are given by the FF-I and FF-II schemes, respectively. The vertical line at $x = 0$ labels the $D\bar{D}^*$ threshold.

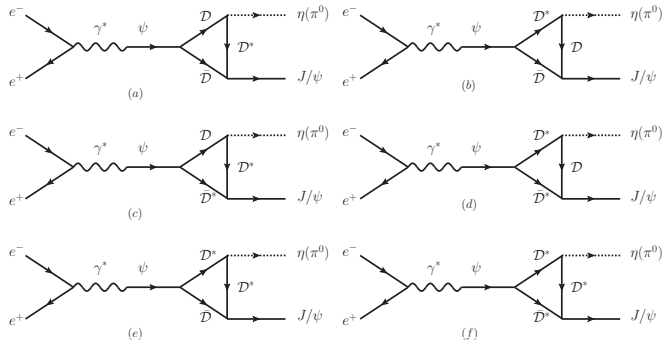


Figure 2. Schematic diagrams for $e^+e^- \rightarrow J/\psi\eta(\pi^0)$ via charmed D (D^*) meson loops. The diagrams for the $\phi\eta_c$ mode are similar.

2.2. Direct evidence for the $D\bar{D}^* + c.c.$ open threshold effects in $e^+e^- \rightarrow J/\psi\pi^0$

Recall that the position of the $X(3900)$ is located between the known $\psi(3770)$ and $\psi(4040)$, its coupling to $J/\psi\eta$ and isospin-violating $J/\psi\pi^0$ would receive relatively small interferences from the nearby resonances. Therefore, peculiar threshold effects due to the open $D\bar{D}^* + c.c.$ might be detectable in $e^+e^- \rightarrow J/\psi\eta$ and $J/\psi\pi^0$ and distinguish this structure from a resonance nature.

Apart from this anticipation, we also consider the $\phi\eta_c$ channel, of which the threshold is very close to the $D\bar{D}^* + c.c.$

As we know from the vector meson dominance (VMD) model, light vector meson contributions to the cross sections are negligible in the charmonium energy region. The main resonance contributions are from vector charmonium excitations. Note that the final states VP consist of a charmonium plus a light meson. Therefore, the transitions are Okubo-Zweig-Iizuka (OZI) rule violating processes, which should be dominated by soft mechanisms near threshold. Since the pure electromagnetic (EM) transitions are negligibly small, a natural way to recognize the soft mechanisms for $e^+e^- \rightarrow J/\psi\eta$, $J/\psi\pi^0$ and $\phi\eta_c$ is via the open charm transitions which are illustrated by Fig. 2. Similar approach has been applied to the study of the cross section lineshape of $e^+e^- \rightarrow \omega\pi^0$ in the vicinity of the ϕ meson mass region [15].

The effective Lagrangians for the coupling vertices involving charmonia and charmed mesons are extracted from heavy quark effective theory and chiral symmetry as applied in Ref. [16, 17, 18]. They are written as follows:

$$\mathcal{L}_2 = ig_2 \text{Tr}[R_{c\bar{c}} \bar{H}_{2i} \gamma^\mu \overleftrightarrow{\partial}_\mu \bar{H}_{1i}] + H.c., \quad (3)$$

where $R_{c\bar{c}}$ denotes the S -wave charmonium states, and H_{1i} and H_{2i} are the charmed and anti-charmed meson triplet, respectively. The Lagrangian describing the interactions between light meson and charmed mesons reads

$$\begin{aligned} \mathcal{L} = & i\text{Tr}[H_i v^\mu \mathbf{D}_{\mu ij} \bar{H}_j] + ig\text{Tr}[H_i \gamma_\mu \gamma_5 A_{ij}^\mu \bar{H}_j] + i\beta\text{Tr}[H_i v^\mu (V_\mu - \rho_\mu)_{ij} \bar{H}_j] \\ & + i\lambda\text{Tr}[H_i \sigma^{\mu\nu} F_{\mu\nu}(\rho)_{ij} \bar{H}_j], \end{aligned} \quad (4)$$

where the operator $A_\mu = \frac{1}{2}(\xi^\dagger \partial_\mu \xi - \xi \partial_\mu \xi^\dagger)$ with $\xi = \sqrt{\Sigma} = e^{iM/f_\pi}$, and $F_{\mu\nu}(\rho) \equiv \partial_\mu \rho_\nu - \partial_\nu \rho_\mu + [\rho_\mu, \rho_\nu]$. M and ρ denote the light pseudoscalar octet and vector nonet, respectively [19, 20].

With the above Lagrangians, the leading order couplings are given as follows [19]:

$$\begin{aligned} \mathcal{L} = & -g_{\mathcal{D}^* \mathcal{D} \mathcal{P}} (\mathcal{D}^i \partial^\mu \mathcal{P}_{ij} \mathcal{D}_\mu^{*j\dagger} + \mathcal{D}_\mu^{*i} \partial^\mu \mathcal{P}_{ij} \mathcal{D}^{j\dagger}) + \frac{1}{2} g_{\mathcal{D}^* \mathcal{D}^* \mathcal{P}} \epsilon_{\mu\nu\alpha\beta} \mathcal{D}_i^{*\mu} \partial^\nu \mathcal{P}^{ij} \overleftrightarrow{\partial}^\alpha \mathcal{D}_j^{*\beta\dagger} \\ & - ig_{\mathcal{D} \mathcal{D} \mathcal{V}} \mathcal{D}_i^\dagger \overleftrightarrow{\partial}_\mu \mathcal{D}^j (V^\mu)_j^i - 2if_{\mathcal{D}^* \mathcal{D} \mathcal{V}} \epsilon_{\mu\nu\alpha\beta} (\partial^\mu \mathcal{V}^\nu)_j^i (\mathcal{D}_i^\dagger \overleftrightarrow{\partial}^\alpha \mathcal{D}^{* \beta j} + \mathcal{D}_i^{*\beta\dagger} \overleftrightarrow{\partial}^\alpha \mathcal{D}^j) \\ & + ig_{\mathcal{D}^* \mathcal{D}^* \mathcal{V}} \mathcal{D}_i^{*\nu\dagger} \overleftrightarrow{\partial}_\mu \mathcal{D}_\nu^{*j} (\mathcal{V}^\mu)_j^i + 4if_{\mathcal{D}^* \mathcal{D}^* \mathcal{V}} \mathcal{D}_i^{*\dagger} (\partial^\mu \mathcal{V}^\nu - \partial^\nu \mathcal{V}^\mu)_j^i \mathcal{D}_\nu^{*j}, \end{aligned} \quad (5)$$

where $\epsilon_{\alpha\beta\mu\nu}$ is the Levi-Civita tensor and D meson field destroys a D meson. All the coupling values have been given explicitly in Ref. [21]. In this study, we include five resonances, i.e. J/ψ , $\psi(3686)$, $\psi(3770)$, $\psi(4040)$, and $\psi(4160)$ which are the dominant ones near the $D\bar{D}^* + c.c.$ threshold.

As mentioned earlier, the reactions $e^+e^- \rightarrow J/\psi\eta$, $J/\psi\pi^0$, and $\phi\eta_c$ via vector charmonium states (denoted as Ψ) involve light hadron productions via soft gluon exchanges. Therefore, they are generally OZI-rule suppressed. In Refs. [22, 23] it is shown that the intermediate meson loops (IML) are relative enhanced in comparison with the soft gluon exchanges for $\psi' \rightarrow J/\psi\eta$ and $J/\psi\pi^0$. As a consequence, the IML provide an mechanism to evade the OZI rule. Nevertheless, it is also an important mechanism for causing strong isospin violations in e.g. $\Psi \rightarrow J/\psi\pi^0$.

The reactions $e^+e^- \rightarrow J/\psi\eta$ and $J/\psi\pi^0$ are correlated with each other as illustrated in Fig. 2. Firstly, the meson loop amplitudes can be separated into two classes, i.e. charged intermediate meson loops (CIML) and neutral intermediate meson loops (NIML). In the isospin symmetry limit, i.e. $m_u = m_d$, the absolute values of these two amplitudes are always equal to each other. In the isospin conserved channels, such as $\Psi \rightarrow J/\psi\eta$, these two amplitudes would add to each other, while in the isospin-violating channels, such as $\Psi \rightarrow J/\psi\pi^0$, these two amplitudes would

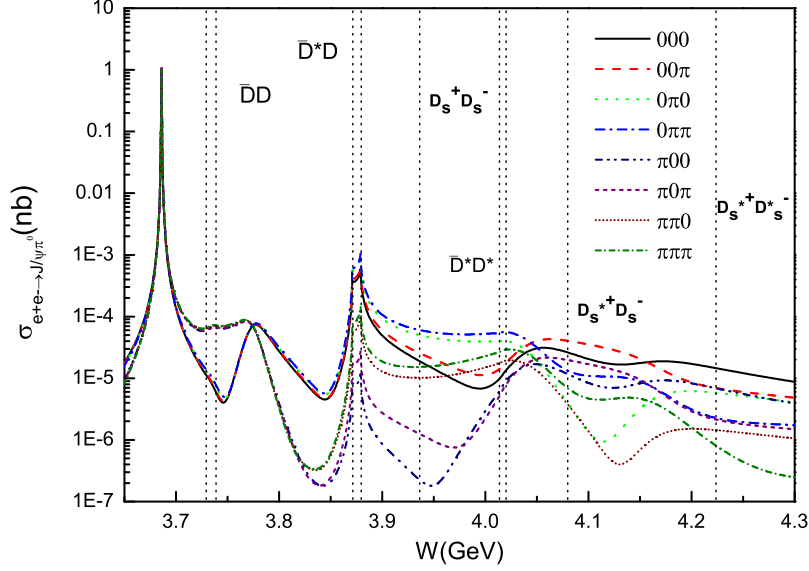


Figure 3. The predicted cross section for $e^+e^- \rightarrow J/\psi\pi^0$ in terms of the c.m. energy W with different phase angles [21]. The vertical lines labels the open charm thresholds.

have different signs and thus cancel each other. In another word, in the isospin symmetry limit, the cross section via the intermediate meson loops would vanish in $e^+e^- \rightarrow \Psi \rightarrow J/\psi\pi^0$.

In reality, the isospin symmetry is broken, i.e. $m_u \neq m_d$. Consequently, the masses of the charged and neutral D (D^*) mesons are different. This will lead to nonvanishing cross sections for $e^+e^- \rightarrow \Psi \rightarrow J/\psi\pi^0$ due to the incomplete cancelations between the CIML and NIML amplitudes. As a prediction for such a scenario, the residual cross sections will appear in between the charged and neutral $D\bar{D}^*$ thresholds and produce two cusps at the thresholds of $W = m_{D^0} + m_{\bar{D}^{*0}} = 3871.79$ MeV and $W = m_{D^\pm} + m_{\bar{D}^{*\mp}} = 3879.85$ MeV. Namely, the mechanism that causes the cross section enhancement between those two thresholds is also responsible for the $X(3900)$ observed in $e^+e^- \rightarrow D\bar{D}$ [9].

In Fig. 3, the calculated cross section for $e^+e^- \rightarrow J/\psi\pi^0$ in terms of the c.m. energy W is presented. Although the cross section is rather sensitive to the relative phases introduced among the transition amplitudes, the peak structure $X(3900)$ has a model-independent feature and can be searched for in experiment. More importantly, since the thresholds of $D^0\bar{D}^{*0} + c.c.$ and $D^+D^{*-} + c.c.$ are isolated from the known $\psi(3770)$ and $\psi(4040)$, the enhancement here would be a clear evidence for non-resonant peaks in e^+e^- annihilations. In contrast, as shown in Ref. [21], although the $D\bar{D}^* + c.c.$ loops have relatively large contributions to the cross sections in $e^+e^- \rightarrow J/\psi\eta$, their contributions are submerged by other amplitudes and cannot be indisputably identified in the cross section lineshape.

We also note that the $\psi(3686)$ has a predominant contribution to $e^+e^- \rightarrow \Psi \rightarrow J/\psi\pi^0$ due to its strong isospin violation couplings via the D meson loops [22, 23]. Such a resonant enhancement should be detectable, and the cross section measurement will provide a calibration for the $X(3900)$ structure.

It should be pointed out that the $X(3900)$ as the open charm effect is a collective one from the $D\bar{D}^* + c.c.$ loops to which all the vector charmonia have contributions. That is why

such a P wave configuration between $D\bar{D}^* + c.c.$ can produce the significant enhancement in $e^+e^- \rightarrow J/\psi\pi^0$. This mechanism is much likely to be different from the $X(3872)$, which has been broadly investigated in the literature as a dynamically generated $D\bar{D}^* + c.c.$ bound state in the relative S wave. Detailed results for $e^+e^- \rightarrow J/\psi\eta$ and $\phi\eta_c$ can be found in Ref. [21].

3. Summary

In summary, we have proposed to study the coupled channel effects in e^+e^- annihilating to $J/\psi\eta$, $J/\psi\pi^0$ and $\phi\eta_c$. In particular, we show that the reaction $e^+e^- \rightarrow J/\psi\pi^0$ will be extremely interesting for disentangling the resonance contributions and open charm effects taking the advantage that the open $D\bar{D}^*$ threshold is relatively isolated from the nearby known charmonia $\psi(3770)$ and $\psi(4040)$. Although we also find that the predicted cross sections are rather sensitive to the model parameters adopted, we clarify that the open charm effects from the $D\bar{D}^* + c.c.$ channel are rather model-independent. Therefore, it is extremely interesting to search for the predicted enhancement around 3.876 GeV (i.e. $X(3900)$) in experiment. Confirmation of this prediction would allow us to learn a lot about the nature of non-pQCD in the charmonium energy region, and provide insights into some of those long-standing puzzles in charmonium decays, such as the “ ρ - π puzzle” and $\psi(3770)$ non- $D\bar{D}$ decays etc [24].

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References

- [1] Olsen S L 2009 arXiv:0909.2713 [hep-ex]
- [2] Voloshin M B 2008 *Prog. Part. Nucl. Phys.* **61** 455
- [3] Eichten E *et al* 2008 *Rev. Mod. Phys.* **80** 1161
- [4] Brambilla N *et al* 2010 arXiv:1010.5827 [hep-ph]
- [5] Appelquist T *et al* 1975 *Phys. Rev. Lett.* **34** 365
- [6] Godfrey S and Isgur N 1985 *Phys. Rev. D* **32** 189
- [7] Barnes T *et al* 2005 *Phys. Rev. D* **72** 054026
- [8] Nakamura K *et al.* [Particle Data Group] 2010 *J. Phys. G* **37** 075021
- [9] Pakhlova G *et al.* [Belle Collaboration] 2008 *Phys. Rev. D* **77** 011103
- [10] Eichten E *et al* 1980 *Phys. Rev. D* **21** 203
- [11] Abe K *et al.* [Belle Collaboration] 2007 *Phys. Rev. Lett.* **98** 092001
- [12] Aubert B *et al* [BABAR Collaboration] 2009 *Phys. Rev. D* **79** 092001
- [13] Zhang Y J and Zhao Q 2010 *Phys. Rev. D* **81** 034011
- [14] Zhang Y J and Zhao Q 2010 *Phys. Rev. D* **81** 074016
- [15] Li G, Zhang Y J, and Zhao Q 2009 *J. Phys. G* **36** 085008
- [16] Liu X H and Zhao Q 2010 *Phys. Rev. D* **81** 014017
- [17] Liu X H and Zhao Q 2011 *J. Phys. G* **38** 035007
- [18] Wang Q, Liu X H and Zhao Q 2010 arXiv:1010.1343 [hep-ph]
- [19] Cheng H Y, Chua C K and Soni A 2005 *Phys. Rev. D* **71** 014030
- [20] Casalbuoni R *et al* 1997 *Phys. Rept.* **281** 145 [arXiv:hep-ph/9605342].
- [21] Wang Q, Liu X H and Zhao Q 2011 *Phys. Rev. D* **84** 014007.
- [22] Guo F K, Hanhart C and Meissner U G 2009 *Phys. Rev. Lett.* **103** 082003; 2010 Erratum-ibid. **104** 109901
- [23] Gu F K, Hanhart C, Li G, Meissner U G and Zhao Q 2011 *Phys. Rev. D* **83** 034013
- [24] Zhao Q 2010 *Nucl. Phys. B (Proc. Suppl.)* **207/208** 347